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Flue Gas Desulfurization Pilot Study. Phase I Survey of Major Installations. Appendix 95-K Carbon-Adsorption Flue Gas Desulfurization Process

NATO Committee on the Challenges of Modern Society, Brussels (Belgium)

Jan 79

PB 295012

NATO CDSM OTAN CCMS

COMMITTEE ON THE CHALLENGES OF MODERN SOCIETY

Flue Gas Desulfurization Pilot Study Phase I — Survey of Major Installations - Carbon-Adsorption Flue Gas Desulfurization Process

Appendix 95-K

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This process employs cross-flow adsorption as the Bergbau Forschung Process and regeneration by hot inert gas as the Rheinluft Process. A pilot plant (10,000 m^3/h) was tested in 1969. Since 1972 a 260,000 m^3/h demonstration unit has been operating at Kensai's Sakai Port power station.

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NATO-CCMS STUDY

PHASE I

Flue Gas Desulfurization Pilot Study Phase I

Survey of Major Installations - Carbon-Adsorption Flue Gas Desulfurization Process

APPENDIX 95-K

Lead Country - Federal Republic of Germany

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January 1979

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Summary

The use of activated carbon or other adsorbents to remove sulfur oxides from flue gases is a promising alternative to the wet scrubbing technology.

The SO_2-rich gas separated from the flue gases allow subsequent production of sulfuric acid or elemental sulfur. The output of salable products eliminates land requirements for waste disposal.

There is not as much large-scale experience as with lime scrubbing processes. The largest unit so far (260,000 m^3/h) has been operated in Japan.

Apart from advancing the solids handling systems and optimizing the process design, the R+D efforts aim at investigating the behavior of the adsorbent with respect to attrition, poisoning of the active surface and self ignition.

Advantages

(1) No scaling or plugging in the adsorber.
(2) Most of the construction material is carbon steel.
(3) Clean fan operation.
(4) NO_x removal (partial).
(5) Fly ash removal.
(6) No need for stack gas reheating.
(7) No waste disposal pond required.

Disadvantages

(1) Deterioration of circulating sorbent through physical and chemical influences.
(2) Large equipment (sorption and desorption vessels) compared with lime scrubbing.

The questionnaires distributed for this study were returned with inadequate information, so that the evaluation necessarily is incomplete, especially with respect to cost aspects. The individual questionnaire data of all plants has been compiled in Table 6 (see appendix) in order to provide an overall survey.

This process employs cross-flow adsorption as the Bergbau Forschung Process and regeneration by hot inert gas as the Rheinluft Process. A pilot plant (10,000 m^3/h) was tested in 1969. Since 1972 a 260,000 m^3/h demonstration unit has been operating at Kansai's Sakai Port power station.

The main drawback in the development of carbon adsorption processes with dry regeneration was the behavior of the carbon with respect to attrition, poisoning of the active surface by fly ash and unreactive compounds, and self-ignition of the carbon in the sorption section.

In the Reinluft Process the respective carbon cost was reduced by using relatively cheap coke from peat and lignite, whereas for the Bergbau Forschung Process a coke was made from hard coal, which is relatively attrition-resistant and has a high ignition temperature.

2. General Process Description

The principles of all dry adsorption systems are essentially the same. The use of activated carbon or other sorbents allow removing of adsorbed compounds by simple thermal stripping. A problem is the oxidation of SO_2 catalyzed by the highly activated surface of the adsorbent. SO_2 reacts with moisture in the gas forming H_2SO_4 in the pores of the adsorbent. Thus one of the main problems is getting the acid out of the pores.

The sorption process of SO_2 by activated carbon can be both chemical and physical. The main chemical reactions and operating parameters are collected in Table 1. A generalized flow diagram is shown in Figure 1. More detailed process information and flow diagrams are collected in the appendix (Section 7).

Coming from the boiler the flue gas enters the adsorber where - in the modern processes - it is brought into contact with activated coke. The desulfurized flue gas passes to the stack directly, while the loaded carbon is transferred to the desorber vessel. By means of heat the SO_2-rich gas is set free and flows to a Claus plant. The regenerated carbon is filled up with make-up coke and recycled to the adsorber.

There are different ways of bringing heat into the desorber: one is to introduce a hot gas into the desorber, another to mix the loaded adsorbent with hot sand (the latter is done in the Bergbau Forschurg Process). As auxiliary equipment there is a screening device which separates friction fines and - in the case of the Bergbau Forschung Process - the heat carrier sand from the recycle coke.

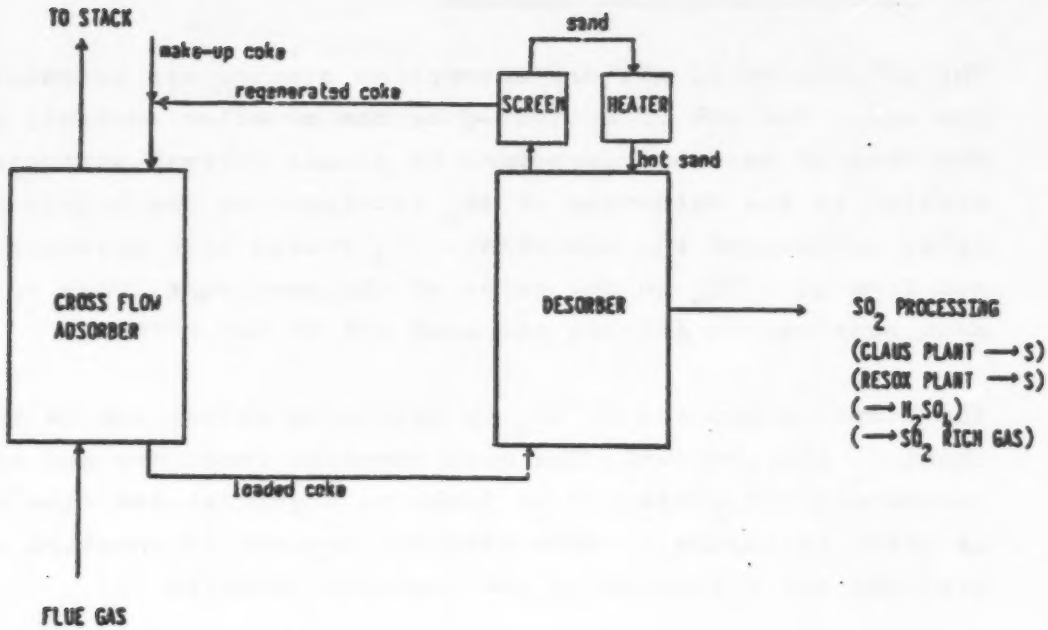

Figure 1: Generalized flow diagram /carbon adsorption

Table 1: BASIC CHEMISTRY AND PROCESS DATA

Chemical Reactions	**Adsorption Section**
	$SO_2 + H_2O + O_2 \longrightarrow$ adsorption
	$SO_2 + H_2O + 1/2\ O_2 \xrightarrow[\text{char coal}]{120\text{-}140\ ^\circ C} H_2SO_4$
	Regeneration Section
	$2H_2SO_4 + C \xrightarrow[\text{sand}]{260\text{-}700\ ^\circ C} CO_2 + 2H_2O + 2SO_2$
Control Theory	Commercial application of hot sand causes a heating rate of 500 °C per minute.
Reaction Kinetics	The maximum reaction rate occurs in the temperature range of 520-680 °C. The reaction in the regeneration section is practically complete at 450 °C.
Agent Requirement	Loading: 5-15 weight % SO_2 Regeneration: SiO_2 : C = 4 : 1
Quality of Flue Gases (in→out)/ Removal Efficiencies	SO_2: 1000...2300 → 200...600 ppm particulate: 150→25 mg/m³ NO_x: R: 15...60 % Cl^-, F^-: R: 50 %
Adsorption Agent	carbon > 90 %, special activated coke, prepared by air oxidation of a fine ground hard coal
Product	regenerator off gas: 20-30 % SO_2, 50-60 % H_2O, 20-30 % (N_2 + CO_2)
Effluents, Waste Streams	no waste
Gas Reheat	no reheat
Subsequent Processing	Bergbauforschung: Claus Process Foster-Wheeler: RESOX Process: crushed coal is the reducing agent at 650-815 °C $SO_2 + C \xrightarrow[1\ bar]{650\text{-}815\ ^\circ C} S + CO_2$ $5SO_2 + H_2O + 7C \rightarrow 5CO_2 + S_{liq.} + H_2S + COS + CS_2$ (SO_2 rich gas → $SO_{2\ Liq.}$ or H_2SO_4)

R = Removal Efficiency

3. Current Status and Plans

The design of the desulfurization reactors as applied in the demonstration plants mentioned under Section 1 and described under Section 7 of this report has proved its value through extensive tests performed since 1974. The circular silo desulfurization reactor for 150,000 m^3/h tested at Lünen may be increased in size for a capacity of 650,000 m^3/h and the two stage reactor (Foster-Wheeler) in a modular fashion may be increased to any size.

Heat transfer by means of solid matter for regeneration of activated char loaded with sulfuric acid was successful. The extension of the sand circuit for flue gas desulfurization units, matched to a power station capacity of 350 MW does not constitute a technical problem.

Since the adsorption and regeneration techniques were given first attention during the initial phases of experimental operation, experiments with the subsequent processing of the SO_2-rich gas have been emphasized in 1977.

The design and operating mode of the Lünen Claus unit has been adjusted to the particular composition of the SO_2-rich gas.

Dry separators for chlorine, fluorine and dust have solved corrosion and catalyst poisoning problems. Also with respect to catalyst saving the Claus plant does not fully follow the peak-shaving operations of the power plant. It continues operating under partial load during week-end shut-downs of the power station using the char charge of the desulfurization unit as a buffer of loaded adsorption agent.

The basic feasibility of directly reducing SO_2 to S using coal as reductant (as done in the Resox Process) was demonstrated.

Current plans extend to investigating the general processing of SO_2-rich gas and also the possibility of NO-separation under conditions prevailing in flue gas desulfurization.

A survey on the current status of carbon adsorption systems in general is given by Table 2. Table 3 shows status details on the two plants considered in this study.

Total Number of Systems in Operation	1
Total Number of Systems Built	3
Total Number of Systems Surveyed	2
Year First Placed in Commercial Service	(1974)
Number of Utility Systems Using Process	-
Total MW of these Facilities	(70)
Number of Industrial Combustion Systems	-
Range of SO_2 Removal Efficiencies (%)	74- 80
Range of Fly Ash Removal Efficiencies (%)	80-100
Range of Availability Factors (%)	-

Table 2: Summarized Status of Carbon Adsorption Systems

Name of Plants Considered in this Study	1) Gemeinschaftskraftwerk Ost, STEAG A.G.	2) Scholz steam plant Gulf Power Company
Location	Lünen, Germany	Chattahoochee, Fla., USA
Type of Respective Power Plant	coal-fired / peaking	coal-fired
Size (MW)	350	40
Fuel Characteristics (type/ % S)	char / 1.23	coal / 0.9-5.0
Heat value (kJ/kg)	22,200	26,700-32,800
Flue Gas Treated (m^3/h/ % of total)	150,000 / 14	73,000 / 50
Year FGD System Started	7/1974	5/1976
Energy Required (MW)		
SO_2 Removal Efficiency (%)	80	74.5
Treatment of Other FG Components (% R.)	particulate: 80; NO_x, Cl, F: 50	
Disposition of End Products	sulfur	sulfur
Average Availability (%/year)	-	-

Table 3: Status of Surveyed FGD Installations

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m^3/h = m^3/h under normal conditions (0 °C, 1 bar)

* R. = % Removal

4. Recent Development and Solutions to Problem Areas

Through extensive development and test programs in recent years with carbon adsorption units in the US, Japan and Germany, good progress was achieved on solving the classic problems of this technology like excessive char consumption, char and gas distribution, plant instrumentation and solids handling systems.

Bergbau Forschung developed a suitable activated char, based on hard coal. This activated char is characterized by a high abrasion resistance, a particle size (Ø 9 mm) that guarantees low pressure drop in the adsorber, a very low reactivity with oxygen and a high SO_2 adsorptive capacity.

The travelling bed adsorber with traverse gas flow as applied in the Bergbau Forschung Process along with the a.m. low pressure drop char eased the solids/gas distribution problems.

Modification or change of gas shut-off valves and solids handling components, both of which had been subject to severe wear by mechanical, thermal and corrosive influences and plugging problems improved the reliability of the systems.

5. Cost

The questionnaires were returned with inadequate information especially with respect to cost (data from questionnaires are underlined in Table 4); the data in Table 4 are therefore only approximate values, lacking information having been taken from other sources /1, 2, 3, 6/.

Capital costs are partly inflated to the year 1976 using a plant cost index from Chemical Engineering (1957 - 59 = 100; 1972 = 137.2; 1973 = 144.1; 1974 = 165.4; 1975 = 182.4; Jan. 1976 = 187.1.). For evaluating fixed costs per year, a fixed charge factor of 15 % has been assumed for each plant, if no other data have been reported.

Total costs per kWh are subdivided in costs per

- 4000 operating hours p.a.
- 8000 operating hours p.a.

---

1 US $ = 300 Yen
1 US $ = 2.40 DM

	BERGBAUFORSCHUNG	BERGBAUFORSCHUNG FOSTER WHEELER
	GKW OST/LÜNEN (49 MW)	SCHOLZ STEAM PLANT (20 MW)
	Total / per kW	Total / per kW
1. Reported capital costs ($) year Costs inflated to 1976 ($)	<u>2,167,000</u> / 44,2 1974 2,450,000 / 50.0	25-35 (low sulfur) 70-75 (high sulfur)
2. Reported annual costs ($) Total fixed costs (fixed chage factor) Total variable costs	367,500 (15 %) 623,000 /3/	
3. Boiler operation hours /capacity factor Generated MWh, p.a.	3700/42.4% 181,300	
4. Reported cost per kWh (mills) : Fixed costs (boiler operation hours) Variable costs	2.02 (3700 h) 0.94 (8000 h) 3.44	
Total costs per kWh 4000 h (mills) 8000 h	5.5 4.4	

<u>Table 4:</u> Cost Data (data reported in the questionnaires are underlined)

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Visit of 14.4.1977 (Dr. N. Haug, Dr. G. Weisser)

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7.1. Conversion Factors

multiply		by	to obtain
feet	x	0.30480	m
cub.ft.	x	28.317	l
Btu/lb	x	0.55554	kcal/kg
	x	2.32593	kJ/kg
Btu/h	x	$0.29300 \cdot 10^{-3}$	kW
a.c.f.m. (act. cub.ft. per min.)	x	1.6992	m^3/h
$lb/10^6$ Btu	x	1.80005	mg/kcal
	x	0.42993	mg/kJ
g.p.m.	x	3.78541	ltr/min
(gal. per min.)	x	0.22712	m^3/h
gal/1000 ft^3	x	0.13368	ltr/m^3
ft^3/min	x	1.6992	m^3/h
kcal	x	4.1868	kJ (J = Ws)
kcal	x	$1.163 \cdot 10^{-3}$	kWh
std. cub. ft per min.	x	1.60776	m^3/h (0 °C/1 bar)
grains/ft^3	x	2.288	g/m^3
grains/std. ft^3	x	2.4182	g/m^3 (0 °C/1 bar)
in (inches) water	x	2.54	mbar
grain	x	0.0648	g
ton (short)	x	0.9072	t

1 MW corresponds to 2,800 - 3,500 m^3/h flue gas (depending on excess air)

1 std. cub. ft = 28.317 l (60 °F / 14.7 psia)
(15.5 °C/ 1 bar)
= 26.796 l (0 °C/ 1 bar)
= 0.026796 m^3

$$\varrho_{SO_2} = 2.927 \text{ g/l}$$

Table 5: Conversion factors used in this study

Table 6: Questionnaire Data

	BERGBAU FORSCHUNG	BERGBAU FORSCHUNG FOSTER WHEELER
	GKW OST/LÜNEN	SCHOLZ STEAM PLANT
1. GENERAL DESCRIPTION		
1.1 Company	Bergbau-Forschung GmbH, Deutsche Babcock AG, Steag AG	Gulf Power Company Foster Wheeler
1.2 Plant name	Gemeinschaftskraftwerk Ost (GKW Ost) der Steag AG, Lünen	Scholz Steam Plant No. 2.A.
1.3, Preparers name and mailing address	Dr. Karl Knoblauch 43 Essen, Frillendorfer Str. 351, W.-Germany phone: (0201) 10 59 225	T.W. Day 11499 Chester Rd., Cincinnati, Ohio 45246 phone: 513-782-4700
1.4 Principal plant products	power	power
Brief description of area surrounding plant site and factors for choice of FGD system	Located on the north-eastern skirt of the Ruhr Industrial Area 30 km north of the city of Dortmund, surrounded by both industrial and agricultural facilities in flat land.	Located appr. 3 km west of the Apalachicola River in Jackson County, Fla., surrounded by a sparcely populated rural area, midway between two small towns.
1.5 Plant location	Lünen	Chattahoochee, Fla.
1.6 STATION CAPACITY		
1.6.1 Total boiler generating capacity (MW)/number of boilers	350/1	40/2
1.6.2 Capacity served by FGD system(MW)	49	20
amount of flue gas treated (m^3/h)	150,000	73,000
% of boiler flue gas treated by FGD system	14	50
Number of boilers served	1	1

m^3/h = m^3/h (0 °C, 1 bar)

MW = electric power generated

N/A = not available

		BERGBAU FORSCHUNG	BERGBAU FORSCHUNG FOSTER WHEELER
		GKW OST/LÜNEN	SCHOLZ STEAM PLANT
1.7	TYPE OF FGD SYSTEM	carbon adsorption	carbon adsorption
1.8	Number of scrubber trains in parallel	1	2
1.9	FGD system installed on new or existing boiler	exist.	exist.
1.10	STATUS OF FGD SYSTEM operational or under construction, date started	operat. 7/74	operat. 5/76
2.	BOILER DATA		
2.1	Boiler identification number	GKW OST 1	No. 2
2.2	Maximum continous heat input (MW)		139
2.3	Max. cont. net generating capacity (MW)	340	47.5
2.4	Flue gas flow rate (m^3/h) temperature at induced draft fan	1,100,000 120-150°	290,000 164°
2.5	Boiler manufacturer	Deutsche Babcock AG	Babcock u. Wilcox
2.5.1	Fuel type	coal	coal
2.5.2	Firing configuration	slag tap furnace	pulverized coal
2.6	Year placed in service	1970	1953
2.7	Type service	peaking	
2.8	Stack height (m)	250	46
2.8.1	Flue gas exit velocity (m/s)	16.2	
2.9	Average boiler operation (h/a)	5530/1976	
2.10	Average boiler capacity factor	42.4 %	

	BERGBAU FORSCHUNG	BERGBAU FORSCHUNG FOSTER WHEELER
	GKW OST/LÜNEN	SCHOLZ STEAM PLANT
2.11 COAL COMPOSITION		
2.11.1 Lower heating value (kJ/kg) (kcal/kg)	22,190 5,300	26,750-32,795 6,389- 7,833
2.12.2 Sulfur content (%)	1.23	0.9-5.0
2.11.3 Ash content (%)	22.4	14.0
2.11.4 Chloride content (%)	(0.2)	0.02-0.15
2.11.5 Moisture (%)	8	15.0
2.12 OIL COMPOSITION	none	none
2.12.1 Grade / heating value (kJ/kg) (kcal/kg)		
2.12.2 Sulfur content (%)		
2.12.3 Ash content (%)		
2.12.4 Chloride content (%)		
2.13 PARTICULATE REMOVAL EQUIPMENT NOT PART OF FGD SYSTEM		
2.13.1 Type	elst. precip.	elst. precip.
2.13.2 Manufacturer	Lurgi	Buell
2.13.3 Efficiency, % removal		99.7
2.13.4 Emission rate (mg/m^3)	150	

	BERGBAU FORSCHUNG	BERGBAU FORSCHUNG FOSTER WHEELER
	GKW OST/LÜNEN	SCHOLZ STEAM PLANT
3. EMISSION REGULATIONS		
3.1 ATMOSPHERIC EMISSIONS		
3.1.1 SO_2	5200 mg/m^3	2.16 mg/kcal
3.1.2 Particulate	150 mg/m^3	0.18 mg/kcal
3.1.3 NO_x		1.26 mg/kcal
3.1.4 Other		
3.1.5 Legal basis	Land NRW "Technische Anleitung Luft"	Florida State Code
3.2 RESTRICTIONS APPLICABLE TO LIQUID OR SOLID WASTES LEGAL BASIS	waste water, pH 5 8-8.6, SS 10 ppm, oil 1 ppm, COD: a) 10 ppm from powerst., b) 20 ppm from FGD, agreement with Owase City	
4. FGD SYSTEM INFORMATION		
4.1 Process name	carbon adsorption	carbon adsorption
4.1.1 Supplier or design company	Bergbau Forschung	Bergbau Forschung Foster Wheeler
4.1.2 WHY WAS THIS SYSTEM CHOSEN?	No reheating necessary; high operating flexibility. End product SO_2-rich gas; convertable to elemental sulfur or sulfuric acid.	N/A
4.1.3 PROCESS DESCRIPTION	see text page 7-18	see text page 7-21

	BERGBAU FORSCHUNG	BERGBAU FORSCHUNG FOSTER WHEELER
	GKW OST/LÜNEN	SCHOLZ STEAM PLANT
4.2 SO_2 SCRUBBING AGENT		
4.2.1 Name	activated carbon	activated carbon
4.2.2 Chemical composition		
Components / % by weight	carbon / > 90	carbon / > 90
4.2.3 Stoichiometric requirement	loading: 5-15 % weight SO_2	loading: 5-15 %
4.2.4 Addition rate (kg/h)	1-1.5 % / run	
4.2.5 Particle size (mm)	5-9 mm	
4.3 REGENERATION AGENT		
4.3.1 Name	sand SiO_2	sand SiO_2
4.3.2 Composition		
4.3.3 Stoichiometric requirement	SiO_2 : C = 4 : 1	
4.3.4 Addition rate	0.1 % / run	
4.3.5 Particle size	0.4-0.5 mm	
4.4 SALABLE PRODUCT		
4.4.1 Name	SO_2 - rich gas ⟶ sulfur	sulfur
4.4.2 Chemical composition Components / % by weight	S / > 99	S / 90-95
4.4.3 Amount generated/year (t/a)	4 t/day	4.8 t/day
4.4.4 Sales potential	chem. industry; other products: SO_2 - liquid, H_2SO_4 possible	

	BERGBAU FORSCHUNG	BERGBAU FORSCHUNG FOSTER WHEELER
	GKW OST/LÜNEN	SCHOLZ STEAM PLANT
4.4.5 BY-PRODUCT RECOVERY PROCESS		
Base	Claus plant	Resox plant
Vendor	Davy Power Gas	Foster Wheeler
Process description		
4.4a Intermediate product composition	SO_2-rich gas, 25 % SO_2, 15 % CO_2, 60% Vol. N_2	
4.5 BY-PRODUCT NUMBER 2	none	none
4.6 WASTE STREAMS		
4.6.1 Type of waste	none	none
% water		
4.6.2 Amount generated in one hour at full load (m^3/h)		
4.6.3 Disposal method		
4.6.4 Disposal site and distance from plant (km)		
4.6.5 Potential effects on environment from sludge disposal		
4.7 SLUDGE FIXATION PROCESS	none	none

	BERGBAU FORSCHUNG	BERGBAU FORSCHUNG FOSTER WHEELER
4.8 FGD EQUIPMENT DATA	GKW OST/LÜNEN	SCHOLZ STEAM PLANT
4.8.1 FIRST SCRUBBER		
4.8.1.1 Type	char pellets moving bed	char pellets moving bed
4.8.1.2 Liquid(solid)/gas ratio(l/m^3)		
4.8.1.3 Gas velocity through absorber or scrubber (m/s)	0.3-0.4	
4.8.1.4 Absorbent(adsorbent) flow (m^3/h)	0-10	2400 kg/h
4.8.1.5 Gas flow entering scrubber (m^3/h)	40,000-150,000	73,000
4.8.1.6 Gas temperature (°C)	120-150	93-149
4.8.1.7 Gas composition		
SO_2 in → out (ppm)	1,000 → 200	2,290 → 580
% removal	80	74.5
Particulate in → out(mg/m^3)	150 → 25	
% removal	80	design: 99.7
NO in → out (ppm)		
% removal	15-60	should be removed
CO_2 in → out (ppm)		
Other in → out	Cl, F to 50 %	
4.8.1.8 Material of construction	St 37.2	N/A
4.8.1.9 Type of lining		
4.8.1.10 Adsorbent and sand losses		
4.8.1.11 Number of stages		
4.8.1.12 Packing type and composition		

	BERGBAU FORSCHUNG	BERGBAU FORSCHUNG FOSTER WHEELER
	GKW OST/LÜNEN	SCHOLZ STEAM PLANT
4.8.2 SECOND SCRUBBER		
4.8.2.1 Type	regenerator	regenerator
4.8.2.2 Liquid (solid)/gas ratio (l/m^3)		
4.8.2.3 Gas velocity through absorber or scrubber (m/s)		
4.8.2.4 Absorbent(adsorbent) flow (m^3/h)		2400 kg/h
4.8.2.5 Gas flow entering scrubber (m^3/h)		
4.8.2.6 Gas temperature (^oC)	400 - 500	650
4.8.2.7 Gas composition	inapplicable	inapplicable
SO_2 in → out (ppm)		
% SO_2 removal		
Particulate in → out (mg/m^3)		
% removal		
NO_x in → out (ppm)		
% NO_x removal		
CO_2		
Other		
4.8.2.8 Material of construction	N/A	N/A
4.8.2.9 Type of lining		
4.8.2.10 Number of stages		
4.8.2.11 Packing type and composition		

	BERGBAU FORSCHUNG	BERGBAU FORSCHUNG FOSTER WHEELER
	GKW OST/LÜNEN	SCHOLZ STEAM PLANT
4.8.3 CLEAR WATER TRAY		
4.8.3.1 Type	none	none
4.8.3.2 L/G ratio		
4.8.3.3 Source of water		
4.8.4 DEMISTER		
4.8.4.1 Type	none	none
4.8.4.2 Number of passes (stages)		
4.8.4.3 Material of construction		
4.8.4.4 Method of cleaning		
4.8.4.5 Flow rate during cleanings (m^3/h)		
4.8.4.6 Frequency and duration of routine cleaning		
4.8.5 REHEATER		
4.8.5.1 Type	none	none
4.8.5.2 Heat load (kW)		
4.8.5.3 Heat transfer surface area (m^2)		
4.8.5.4 Temperature of gas in (^0C)		
out (^0C)		
4.8.5.5 Reheater materials of construction		

		BERGBAU FORSCHUNG	BERGBAU FORSCHUNG FOSTER WHEELER
		GKW OST/LÜNER	SCHOLZ STEAM PLANT
4.8.6	SCUBBER TRAIN PRESSURE DROP DATA		
4.8.6.1	First scrubber (mbar)	10-16	N/A
4.8.6.2	Second rubber (mbar)		
4.8.6.3	Clear water tray (mbar)		
4.8.6.4	Demister (mbar)		
4.8.6.5	Reheater (mbar)		
4.8.6.6	Ductwork (mbar)	3-5	
4.8.6.7	Total FGD system (mbar)	13-21	
4.8.6.8	I.D. fan ΔP (mbar)		
4.9	SYSTEM MAKE-UP WATER ADDED (m^3/h)	none	none
4.9.1	Water added per mole of SO_2 removed (m^3/kg mol)		
4.9.2	Source of make-up water		
4.9.3	Where is water added		
4.10	BYPASS SYSTEM		
4.10.1	Can flue gas be pypassed?	yes	N/A
4.10.2	Height of gas discharge when bypassed (m)		
4.11	SLURRY DATA	none	none
	pH/% solids by weight		
4.11.1	Fresh slurry to scrubber		
4.11.2	Recirculating slurry		
4.11.3	Waste slurry		

	BERGBAU FORSCHUNG	BERGBAU FORSCHUNG FOSTER WHEELER
	GKW OST/LUNEN	SCHOLZ STEAM PLANT
4.12 SPENT SLURRY SYSTEM	none	none
4.12.1 Clarifiers		
4.12.1.1 Number		
4.12.1.2 Diameter (m)		
4.12.2 Solid separation		
4.12.2.1 Type		
4.12.2.2 Cloth area (m^2)		
4.12.2.3 Capacity (wet cake) (t/h)		
4.13 SPACE REQUIRED, EXCLUSIVE OF SLUDGE DISPOSAL AREA (m^2)	none	none
4.14 PERSONNEL (man-hours/year)		
4.14.1 Operating		N/A
4.14.1.1 Specialists	16,080	
4.14.1.2 Unskilled	8,040	
4.14.2 Maintenance and repair	5,400	
4.15 ENVIRONMENTAL LOAD		
4.15.1 Waste water treatment process		N/A
4.15.2 Concentrations		
4.15.3 Appearance of flue gas discharge - any mist problems?	no cooling	

	BERGBAU FORSCHUNG	BERGBAU FORSCHUNG FOSTER WHEELER
	GKW OST/LÜNEN	SCHOLZ STEAM PLANT
4.16 FGD SYSTEM OPERATION		
4.16.1 % of boiler load FGD can operate	20-100	N/A
4.16.2 Lag time	simultaneously	
5. ACTUAL COSTS FOR TOTAL FGD INSTALLATION (year)	2.4 DM = 1 $ (1974)	
5.1 CAPITAL COSTS ($)		
5.1.1 Scrubber	750,000	N/A
5.1.2 Absorbent/regeneration system	792,000	
5.1.3 Sludge disposal system	500,000	
5.1.4 Site improvements	125,000	
5.1.5 Land, roads, tracks, substation		
5.1.6 Engineering costs	included	
5.1.7 Contractor's fee		
5.1.8 Interest during construction		
Construction period (months)	14	
5.1.9 License fees		
5.1.10 Other		
5.1.11 Total ($)	2,167,000	
($/kW)	44.22	25-35 (low sulfur) 70-75 (high sulfur)

	BERGBAU FORSCHUNG	BERGBAU FORSCHUNG FOSTER WHEELER
	GKW OST/LÜNEN	SCHOLZ STEAM PLANT
5.2 ANNUAL COSTS ($)		
5.2.1 Interest		N/A
5.2.2 Depreciation		
5.2.3 Insurance and taxes	6,250	
5.2.4 Total fixed costs		
5.2.5 Labor and overhead Average man hour cost cost/year		
5.2.6 Raw material breakdown Unit cost Annual cost		
5.2.7 Utilities, unit cost, annual costs	0.042/kWh	
Electricity	0.042/m^3	
Water	4.17 /t	
Steam	12.5 /Ccal	
Fuel		
5.2.8 Maintenance cost per year		
5.2.9 Other costs, list		
5.2.10 Total variable cost per year	623.000 /3/	
5.2.11 Total annual cost		
5.3 WASTE DISPOSAL COST ($)	nil	nil
Unit cost		
Annual cost		
5.4 BY-PRODUCT CREDIT ($)		
5.4.1 By-product 1	58-71/t sulfur	N/A
5.4.2 By-product 2		

	BERGBAU FORSCHUNG	BERGBAU FORSCHUNG FOSTER WHEELER
	GKW OST/LÜNEN	SCHOLZ STEAM PLANT
5.5 NET ANNUAL COST		
5.5.1 Cost per kWh for last year (mills)	N/A	N/A
5.5.2 Cost per kWh at maximum continous rating (mills)		
5.5.3 Cost per kWh without FGD		
6. ENERGY REQUIREMENTS		
Pumps (kW)	N/A	N/A
Fan (kW)		
Reheat (kW)		
Reductant chemicals (kW)		
Other (kW)		
Total (kW)		
Per Mg of SO_2 removed(kWh/t SO_2)		

	BERGBAU FORSCHUNG	BERGBAU FORSCHUNG FOSTER WHEELER
	GKW OST/LÜNEN	SCHOLZ STEAM PLANT
7. PERFORMANCE HISTORY; OPERATING PROBLEMS AND SOLUTIONS		
7.1 Scrubber system	Adsorber system: protection against power plant induced draft was improved by installation of double butterfly valve. Additionally in case of FGD plant shut-down the coke bed is protected by inert gas.	Absorber system: clear distribution and char level control problematic during start-up. Improvement by installation of a "spider leg" char distribution system, sight glasses and nuclear level detector and thermocouples.
7.2 Demister		
7.3. Reheater		
7.4 Fan		
7.5 Sludge system		
7.6 Regeneration system	Sand/coke ratio had to be optimized. Subsequently plant reached full performance.	Start-up behavior improved by modifying design and control of char feeding, char/sand separation, sand conveying and char cooling equipment.
7.7 By-product system	Peaking service of FGD-plant shortens lifetime of Claus plant catalysts. Problem solved by utilizing adsorber as SO_2-buffer to ensure continous operation of Claus plant.	RESOX-section: start-up problems improved by installation of additional alarm points, and correction of wiring errors on control loops.
7.8 Other		
7.9 Availability	N/A	N/A

7.3. Process Description /14, 12/

7.3.1. Bergbau Forschung Process

The Bergbau Forschung (BF)-process makes use of the well known fact that any carbonaceous adsorbent will remove sulfur dioxide from a gas containing that pollutant. BERGBAU FORSCHUNG has developed a special activated coke for this purpose, which is outstanding in its overall performance, i. e. it is characterized by its high SO_2 adsorption rate, low wear factor and high ignition temperature. This coke can easily be regenerated and is therefore recycled in the BF process, as can be seen from the basic flow diagram.

In the adsorption system① sulfur dioxide is removed from polluted gas streams by adsorption on activated coke. The SO_2-charged adsorbent is then regenerated in the desorption system ② thus producing a gas stream of high SO_2 concentration. For the final step, the processing of the SO_2 rich gas③, we have the option either to produce sulfur of high purity, liquid sulfur dioxide or sulfuric acid.

The polluted gas stream is brought in contact with the activated coke in the adsorption reactor①, which is a cross-stream moving bed reactor. The clean gas is then directly blown to the stack④, i.e. no reheating is required. Since the coke not only removes the SO_2 from the gas but in addition flue dust which has passed the electrical precipitator, this dust together with a small amount of coke fines resulting from wear inspite of the great hardness of the coke, has to be separated from the adsorbent by a screening machine⑤. By bucket elevators⑥ the coke, laden now with sulfur dioxide, is then conveyed to the desorption plant②. The heart of this subsystem is the desorption reactor②, likewise a moving bed reactor. Here the regeneration takes place by heating the adsorbent to an average temperature of 600 °C. Several ways of heating up the coke can be thought of. At present it is being done by mixing the coke in the reactor directly

with sand as a solid heat carrier. This sand is heated and at the same time conveyed by combustion gases of a separate combustion chamber[7] in the so-called sandlift[8]. The waste heat of these combustion gases is partly recovered in a heat exchanger for air and in the boiler of the power plant.

The regenerated coke discharged from the desorption reactor has to be cooled down[9] to 100 °C once it is separated from the sand by a screening machine[10]. This is being done in two stages with water and air on cooling conveying tracks[9]. The waste heat of this process step is not recovered due to capital investment considerations. Finally the coke is recycled to the adsorption reactor by bucket elevator.[11]

During the regeneration the SO_2-charged coke undergoes a modified reversal of the adsorption reaction yielding an effluent gas with a sulfur dioxide concentration of 25 to 30 % by volume. This gas, after passing a dust separator is blown to the SO_2 processing system.[3] This can be a modified Claus plant for the production of sulfur, a sulfur dioxide liquefaction plant producing SO_2, if necessary of quality required by the food industry, or a sulfuric acid plant. Each of these plants comprise standard technology of the chemical industry.

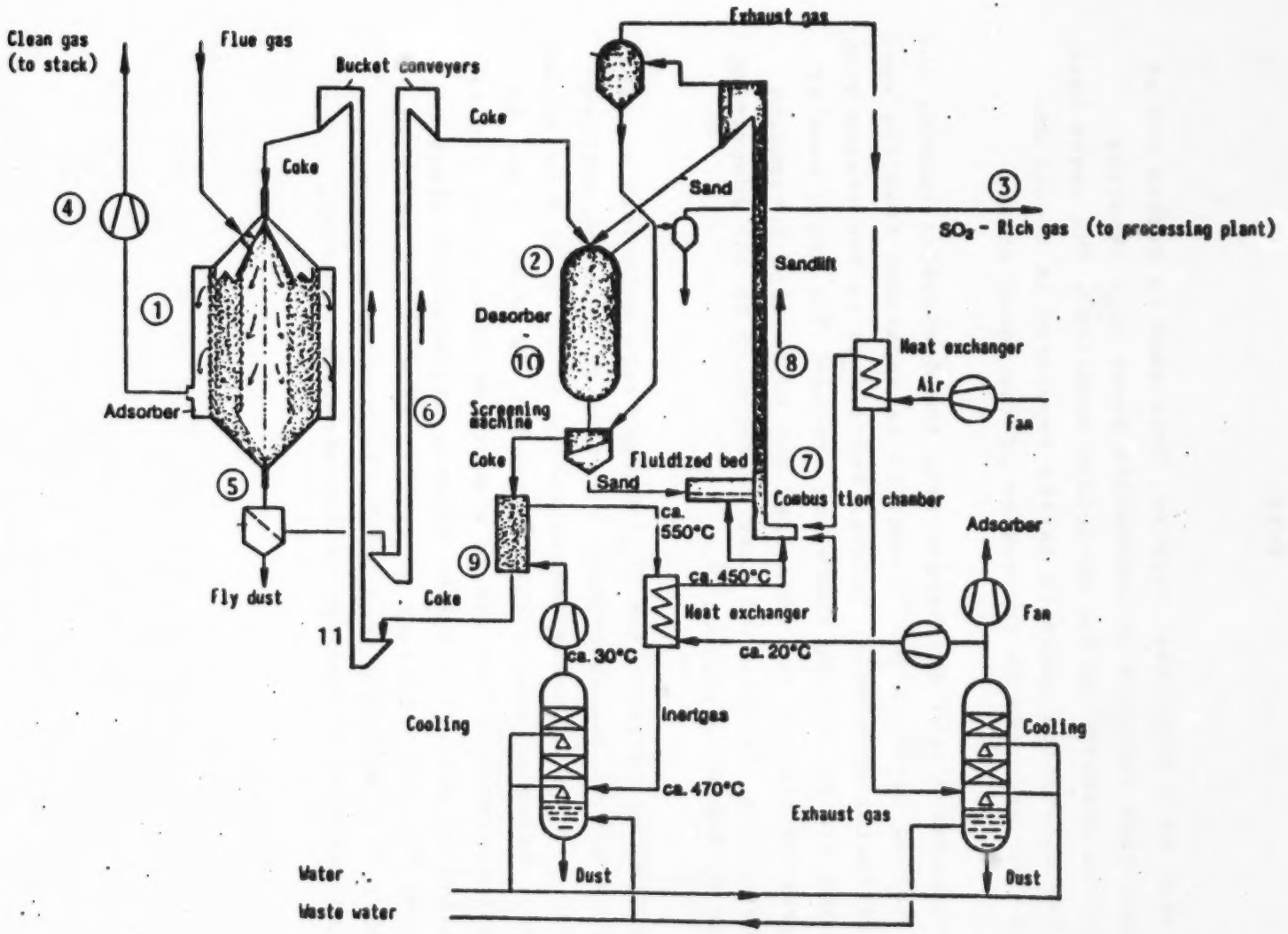


Fig. 2: Flow diagram of the BERGBAU FORSCHUNG Process /12, 14/

7.3.2. Foster-Wheeler/Bergbau Forschung Process /13/

For the BF-process a modified solution was developed by Foster Wheeler with a two-stage adsorber unit and a RESOX plant for further processing of the SO_2-rich gas.

The demonstration unit at the Scholz Steam Plant is a two-stage gas/solid contacting device①② consisting of permanently fixed vertical parallel steel louver beds that support and contain the activated coke. Within the adsorber module the activated coke moves downward in the plug flow contained by the louvers on the gas inlet and exit sides of the adsorber. The polluted gas stream passes in through the louvers, through the adsorbent, and out through the louvers on the opposite side of the adsorber. The sulfur dioxide and other contaminants contained in the gas stream are adsorbed on the activated coke.

Since adsorption efficiency is a function of the percent saturation of the activated coke, the upper sections of the bed are more efficient than the lower sections.

A baffle③ separates the gas that passes through the more efficient upper two thirds of the adsorber from the gas that passes through the lower third.① The gas from the top section discharges directly through the adsorber discharge fan.④ The gas from the lower third, requiring additional sulfur dioxide removal, passes through the smaller 4- by 4-foot second-stage bed②, similar in design and operation to the first stage ① (6- by 6-foot). The gas then passes through a second stage adsorber discharge fan.⑤ The two gas streams then enter a common flue header⑥ and discharge to a separate test stack.

The two-stage design optimizes the quantity of sulfur dioxide adsorbed per unit weight of regenerated char. The individual

sulfur dioxide concentrations of the two gas streams are measured to provide feedback for performance verification and control.

The sulfur dioxide in the gas stream is adsorbed into the pores of the char pellets and then oxidized to sulfuric acid in the presence of oxygen and water vapor in the polluted gas stream. Additionally, the adsorber functions as a panel bed filter to remove particulates from the gas stream.

The adsorbent is regenerated after it has been discharged from the adsorber and is separated from particulates by a vibrating sieve.(7) Regeneration is effected thermally by continuously removing the sulfuric-acid-charged coke from the bottom of the adsorber and transferring it to a reactor vessel(8) where the saturated coke is regenerated by contact with hot sand in an inert reducing atmosphere. The reactions that occurred in the adsorption section undergo a modified reversal in the regenerator vessel which results in the fixed carbon of the adsorbent reducing the entrained sulfuric acid to sulfur dioxide.

Specifically regeneration is effected in a moving bed mass flow reactor vessel(8) employing sand as a direct heat carrier, heating the acid-laden adsorbent to 650°C. The sand is initially heated in a fluidized heater(9) to a temperature of 815°C. The saturated coke, upon mingling with the sand, heats up to a temperature of approximately 650°C, at which point the adsorption reactions are reversed: this results in the formation of water, carbon dioxide, sulfur dioxide, and regenerated coke. The coke is separated from the sand by a bar-type screen(10), cooled(11), and then recycled to the top of the adsorber.(12) The sand is injected into an air lift(13) which reheats the sand and recycles it to the regenerator.

The off-gas rich in sulfur dioxide is then routed to the reduction section, where it undergoes the Foster Wheeler Resox proprietary process (14) by which the sulfur dioxide is reduced to elemental sulfur in a reactor vessel and condensed to a salable by-product.

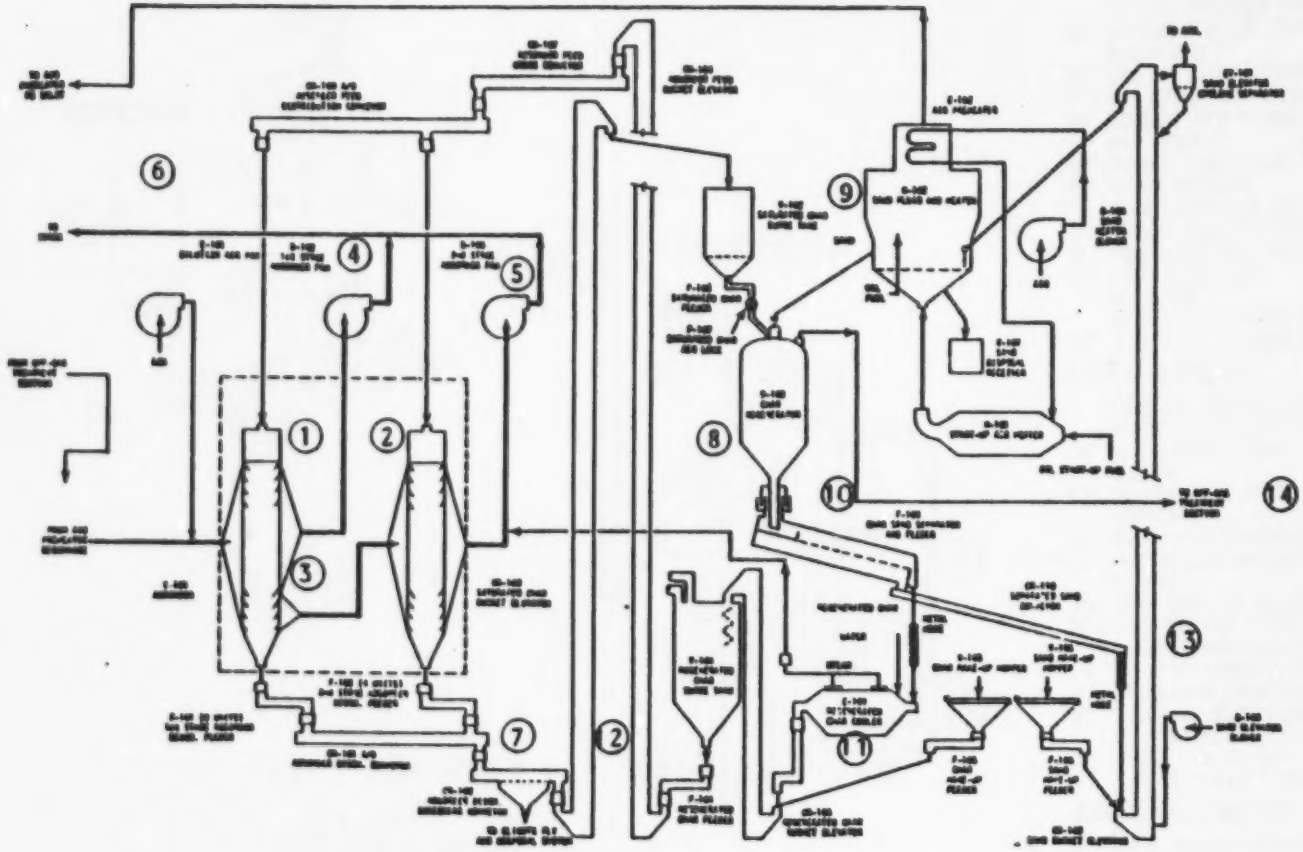
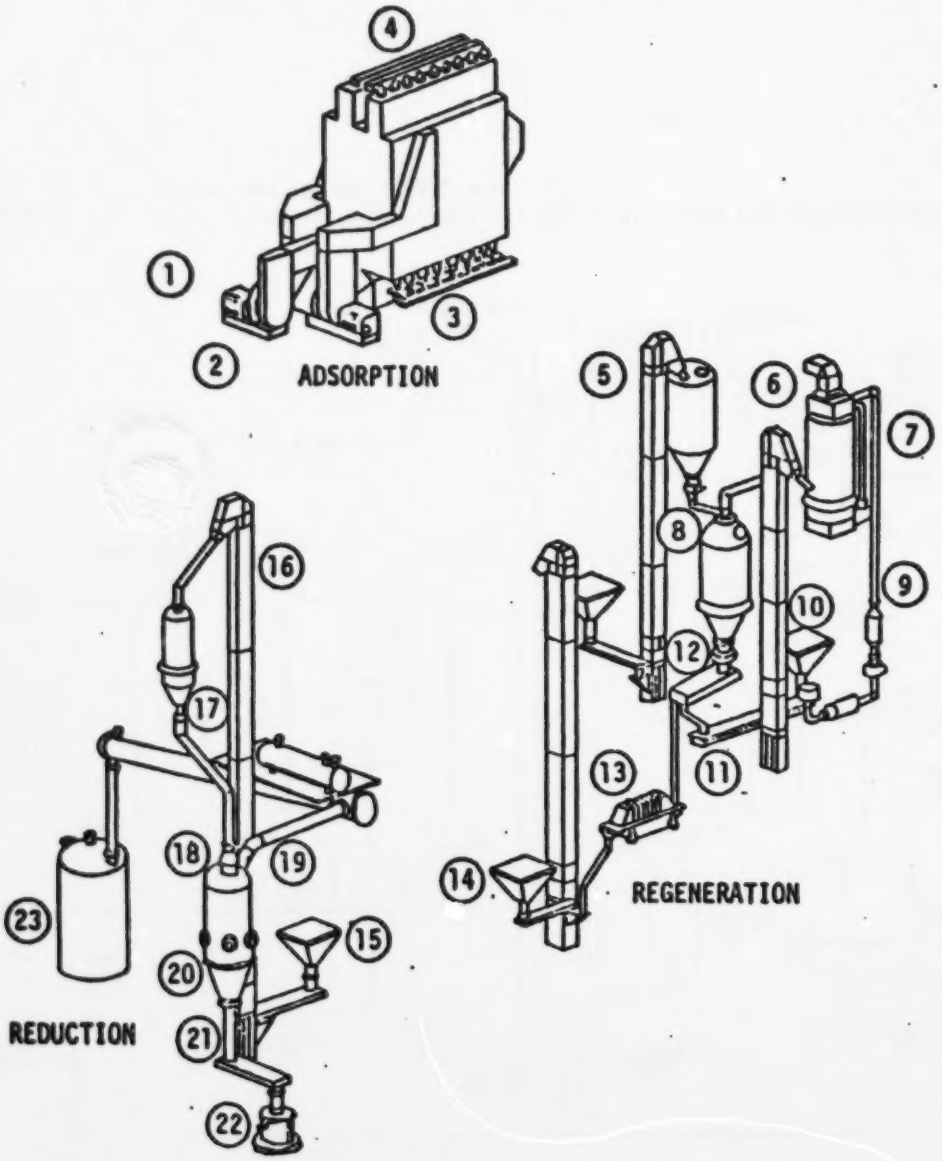


Figure 3: The Foster Wheeler/Bergbau Forschung prototype unit process flow diagram /13/



ADSORPTION SECTION

1. INLET FLUE GAS DUCTING, DILUTION AIR DESIGN, AND ADSORPTION SECTION OVERALL LAYOUT.
2. ADSORPTION DISCHARGE FANS.
3. ADSORBER DISCHARGE FEEDERS CONVEYORS AND SITE GLASSES WHICH SHOW CHAR MOVEMENT.
4. ADSORBER FEED CONVEYORS.
5. CHAR BUCKET ELEVATORS.

REGENERATION SECTION

6. AIR PREHEATER, SAND FLUID BED HEATER, HOT SAND BUCKET ELEVATOR.
7. START UP AIR HEATER.
8. SATURATED CHAR SURGE TANK, SATURATED CHAR FEEDER, REGENERATOR.
9. SAND HEATER BLOWER.
10. SAND MAKE UP HOPPER, FEEDER.
11. HOT SAND CONVEYOR.
12. CHAR-SAND SEPARATOR FEEDER.
13. REGENERATED CHAR COOLER.
14. REGENERATED CHAR BUCKET ELEVATOR, CHAR MAKE UP HOPPER, FEEDER.

REDUCTION SECTION

15. COAL MAKE UP HOPPER, FEEDER FEED BUCKET ELEVATOR.
16. COAL FEED BIN.
17. COAL FEED BIN ACTIVATOR, ROTARY COAL AIRLOCK, RESOX START UP HEATER.
18. RESOX REACTOR.
19. SULFUR CONDENSER, TAIL GAS BLOWER.
20. CONTROL AIR BLOWER.
21. ASH DISCHARGE FEEDER
22. ASH RECEIVER VESSEL, WEIGH SCALE.
23. SULFUR STORAGE TANK, SULFUR TRANSFER PUMP.

Figure 4 : Foster Wheeler/Bergbau Forschung dry adsorption prototype: General equipment schematic. /13/